

The redshift distribution of gamma-ray bursts revisited

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ABSTRACT

In this Letter, we calculate the redshift distribution of gamma-ray bursts assuming that they trace (i) the globally averaged star formation rate or (ii) the average metallicity in the Universe. While at redshifts 5 and below both the star formation rate and the metallicity are observationally determined modulo some uncertainties, at higher redshifts there are few constraints. We extrapolate the star formation rate and metallicity to higher redshifts and explore models that are broadly consistent with bounds on the optical depth from *WMAP* results. In addition, we also include parametric descriptions of the luminosity function, and the typical spectrum for gamma-ray bursts (GRBs). With these essential ingredients included in the modelling, we find that a substantial fraction (75 per cent) of GRBs are expected to originate at redshifts below 4, in variance with some previous estimates. Conversely, if we assume as expected for the collapsar model that gamma-ray bursts favour a low-metallicity environment, and therefore relate the GRB rate to a simple model of the average metallicity as a function of redshift, we find that a higher fraction of bursts, about 40 per cent, originate from $z > 4$. We conclude with the implications of *Swift* GRB detections.

Key words: gamma-rays: bursts.

1 INTRODUCTION

The demonstration that long-duration gamma-ray bursts (GRBs) are related to core-collapse supernovae (Galama et al. 1998; Stanek et al. 2003; Hjorth et al. 2003; Malesani et al. 2004), likely leading to the formation of black holes in ‘collapsars’ (MacFadyen & Woosley 1999), suggests that GRBs trace the deaths (and hence births) of short-lived massive stars. Moreover, as GRBs can be detected to very high redshifts (Lamb & Reichart 2000), unhindered by intervening dust – the current record is $z = 4.50$ (Andersen et al. 2000) – they hold the promise of being useful tracers of star formation in the Universe (Totani 1997; Wijers et al. 1998; Blain et al. 1999; Blain & Natarajan 2000; Ramirez-Ruiz, Trentham & Blain 2002b; Bromm & Loeb 2002; Gou et al. 2004). This ansatz, that GRBs are likely to trace the observed star formation rate (SFR) effectively, has been used to predict the redshift distribution of GRBs, despite our lack of knowledge of SFRs at $z > 6$. Observational estimates of the SFR even at modest redshifts have been plagued by uncertainties arising as a result of correction for dust extinction. Therefore SFRs need to

be extrapolated to higher redshifts. The only current constraints that are useful are the *Wilkinson Microwave Anisotropy Probe* (*WMAP*) estimate of the optical depth and the redshift of re-ionization (Kogut et al. 2003), both of which suggest the existence of ionizing sources out to very high redshifts. The extrapolations of the SFR explored here would provide the requisite number of ionizing photons as demonstrated by Somerville & Livio (2003).

The discovery of several $z \sim 6$ quasars in the Sloan Digital Sky Survey (SDSS) with spectra that are consistent with showing zero flux below Lyman α (a ‘Gunn–Peterson’ trough) indicates that the intergalactic medium (IGM) had a significant neutral fraction at $z > 6$ (Fan et al. 2001; Becker et al. 2001). The ionization history of the Universe has also been constrained via observations of the cosmic microwave background (CMB). The first-year results from the *WMAP* satellite constrain the optical depth to Thomson scattering to be $\tau = 0.17 \pm 0.04$, implying a re-ionization redshift $z_{\text{reion}} = 17 \pm 5$ (Kogut et al. 2003). Our extrapolation of the SFR to higher redshifts is in consonance with these observations.

In this work, we explore a fully self-consistent approach to predict the expected redshift distribution of GRBs at $z > 3$. In Section 2, the observed redshift distribution of GRBs is presented. A clutch of star formation models are studied here, which are then extrapolated to

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higher redshifts. In Section 3, we also investigate the proposition that GRBs progenitors might be preferentially metal-poor as expected in the collapsar model and as suggested by the observations of Fynbo et al. (2003) and Vreeswijk et al. (2004). A model where the GRB rate is inversely correlated with the mean metallicity in the Universe is explored. GRBs are then modelled with a typical spectral shape and a luminosity function, the details of which are presented in Section 4. We conclude with a synopsis and discussion of our results in the context of GRB detections by the *Swift* satellite in Section 5.

2 GRBs: THEIR OBSERVED REDSHIFT DISTRIBUTION AND THE SFR

Despite the ability of spacecraft equipped with GRB detectors to detect GRBs to high redshift (Gorosabel et al. 2004), no very high- z GRB has yet been detected at say, $z > 5$. It is important to note that selection effects are difficult to quantify so the observed distribution may not be the same as the true distribution. Two of the primary causes of selection effects are the lack of knowledge of the intrinsic luminosity function of GRBs and the details of the central engine that drives the bursts, both of which impact the redshift distribution of bursts.

The recent launch of *Swift* promises to detect GRBs *en masse* (Gehrels et al. 2004). It is interesting to note that $z_{\text{median}} = 1.1$ for non-*Swift* bursts, and $z_{\text{median}} = 2.9$ for *Swift* bursts, bolstering hopes that *Swift* may indeed push detection of GRBs more efficiently to higher redshifts. While the calibration of the detection efficiency for *Swift* will be best determined over the next couple of years of operation, for the purposes of this paper we use the detection efficiency model curve for *Swift* adopted by several other authors (Porciani & Madau 2001; Gou et al. 2004; Gorosabel et al. 2004, fig. 3). The detection efficiency curve as a function of redshift that we adopt is overplotted in Fig. 2 (later) (thin solid line).

To what extent do GRBs trace star formation? It has been argued that individual GRBs may trace galaxies or regions of galaxies with high specific star formation (Christensen, Hjorth & Gorosabel 2004; Courty, Bjornsson & Gudmundsson 2004) or low metallicity (MacFadyen & Woosley 1999; Ramirez-Ruiz, Lazzati & Blain 2002a; Fynbo et al. 2003). However, this does not preclude the possibility that GRBs trace the SFR of the Universe in a globally averaged sense. Indeed, the luminosity function (LF) of $z > 2$ GRB host galaxies, assuming that GRBs trace ultraviolet light, and the LF of Lyman-break galaxies are consistent (Jakobsson et al. 2005). We start with the premise that the GRB rate¹ traces the global SFR of the Universe, $R_{\text{GRB}}(z) \propto R_{\text{SF}}(z)$, where $R_{\text{SF}}(z)$ is the co-moving rate density of star formation.

The expected evolution of the globally averaged cosmic SFR with redshift has been studied by many authors, following the first successful attempt by Madau et al. (1996), who based their estimates on the observed (rest-frame) ultraviolet luminosity density of galaxy populations. Using various observational techniques, the cosmic SFR can now be traced to $z \approx 5$, although there is no clear consensus on the details of dust correction at both high and low redshifts (Dickinson et al. 2003; Steidel et al. 2004). In this paper, we explore several models that describe (all shown in Fig. 1) the global SFR per unit co-moving volume. Wherever needed, values for cosmological parameters consistent with the *WMAP* results (Spergel et al. 2003) are assumed: matter density $\Omega_m = 0.3$, baryon density $\Omega_b = 0.044$,

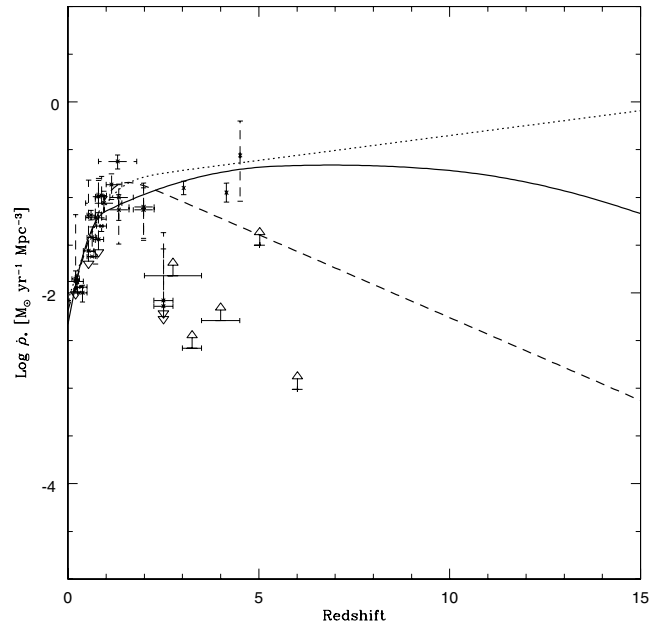


Figure 1. The three star formation models considered in this work: model I (dotted curve); model II, the constructed semi-analytic model (solid curve); and the conservative model III (short-dashed curve). The data points (with error bars) are collated from the literature of measured SFRs from various authors; this particular compilation was taken from a paper by Dickinson et al. (2003) and references therein.

dark energy $\Omega_\Lambda = 0.70$, Hubble parameter $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, fluctuation amplitude $\sigma_8 = 0.9$, and a scale-free primordial power spectrum $n_s = 1$.

The first model studied here (model I hereafter) is similar to one considered previously by Porciani & Madau (2001) which they used in modelling the fraction of lensed GRBs (their model SF3). Our model I (dotted curve in Fig. 1) provides a good fit to the submillimetre determinations of the luminosity density. Blain et al. (1999) have argued that the SFR at all redshifts may have been severely underestimated because of large amounts of dust extinction detected in SCUBA galaxies. In addition, we construct a high-redshift extrapolation for a star formation history (model II, the solid curve in Fig. 1) that is required to fit the observational data at low redshifts and has sufficient star formation at high redshifts ($z > 10$) to match the *WMAP* constraints on the optical depth. We justify this extrapolation with a physical picture in mind using a semi-analytic model, the details of which are described in the following section. Models I and II predict very similar GRB rates although they appear to be divergent at $z > 7$. Finally, as GRBs themselves do not seem to be pointing to large amounts of dust in their host galaxies (Berger et al. 2003; Fynbo et al. 2003; Tanvir et al. 2004; Vreeswijk et al. 2004; Jakobsson et al. 2005), and while this might be a selection effect, we have also considered a model in which the bulk of the star formation is not obscured by dust at $z > 5$ but occurs in a population of numerous very faint galaxies that each may have moderate amounts of dust (our model III). We have used the lower limit on the SFR from observations of Lyman-break galaxies at $z = 5$ to constrain our model III (dashed curve in Fig. 1).

2.1 Constructing model II: a semi-analytic model for high-redshift star formation

We calculate the global SFR density from $z \sim 30$ to 3 using a simple model that combines the rate of dark matter halo growth with

¹ Throughout this paper, GRB rate refers to the GRB occurrence rate and not the detected rate unless explicitly stated.

a prescription for cooling and star formation, and match this rate to observational constraints on the SFR obtained at $3 \lesssim z \lesssim 6$ and at lower redshifts [similar to previous work by Somerville & Livio (2003)]. Prompted by the *WMAP* estimate of the optical depth at reionization, which points to the existence of a significant number of ionizing sources at high redshift (assumed to be stars), we construct a star formation history with vigorous activity at the earliest epochs. This is done in the context of the standard structure formation scenario within the cold dark matter paradigm, where haloes build up hierarchically and galaxies form from the condensation of baryons in dark haloes. A much more sophisticated version of this approach was pioneered (Kauffmann, Guiderdoni & White 1993; Cole et al. 1994), developed and honed over the years by several groups.

With the abundance of dark matter halo masses $n(M, z)$ determined using the Press–Schechter formalism, we then proceed to use a simple cooling criterion to determine the fraction of gas that is converted into stars modulo some efficiency factor² ϵ_* taken to be roughly 10 per cent in these collapsed haloes. Depending on the primary coolant, atomic or molecular, there is a critical mass threshold for the gas content of a dark matter halo to cool, and form stars. The SFR can then be written as follows:

$$\dot{\rho}_* = \epsilon_* \rho_b \frac{df_m}{dt} (M > M_{\text{thres}}), \quad (1)$$

where f_m is the fraction of the total mass in collapsed haloes with masses greater than M_{thres} , obtained from the halo mass function $d n(M, z)/dM$, ρ_b is the mean density of baryons and the efficiency of converting gas into stars is encapsulated in ϵ_* . The threshold mass M_{thres} determines the dominant cooling route; it corresponds to haloes with a virial temperature of about 10^4 K for atomic cooling, and $T \simeq 100$ K for molecular cooling. Using standard cooling arguments and assuming a Salpeter initial mass function (IMF) for the stars formed, the SFR can be computed. The predicted SFR for this model (solid curve in Fig. 1) is then calibrated with observational estimates at ‘low’ redshift $3 \lesssim z \lesssim 6$. Using Somerville & Livio’s estimates for the fraction of ionizing photons available per hydrogen atom given the SFR, we argue that these SFR models are consistent with the optical depth measured by *WMAP* [for further details see section 4.2 of Somerville & Livio (2003)].

2.2 GRB rate and metallicity: exploring a toy model

A larger proportion of the higher redshift GRB host galaxies are detected as Lyman α emitters (Kulkarni et al. 1998; Ahn 2000; Møller et al. 2002; Fynbo et al. 2003; Vreeswijk et al. 2004) compared with galaxies selected by the Lyman-break technique (Shapley et al. 2003) at similar redshifts. This led Fynbo et al. (2003) to suggest a preference for GRB progenitors to be metal-poor as predicted by the collapsar model. In the collapsar model, the presence of a strong stellar wind (a consequence of high metallicity) would hinder the production of a GRB, therefore metal-poor hosts would be favoured sites (MacFadyen & Woosley 1999; Izzard, Ramirez-Ruiz & Tout 2004). Here, we explore a toy model wherein the GRB rate decreases with increasing metallicity. There are observational constraints on the mean metallicity of the Universe as a function of redshift (Pettini 2003); however, for our exploratory purposes it is adequate to consider a simple model (model IV) wherein the GRB rate is modelled just as a step function with higher rate at large redshifts ($z \gtrsim 3$) when the average metallicity of the Universe is low, and taken to

² The requirement to match up with the measured value of the SFR at $z = 0$ constrains the value of ϵ_* to ~ 10 per cent.

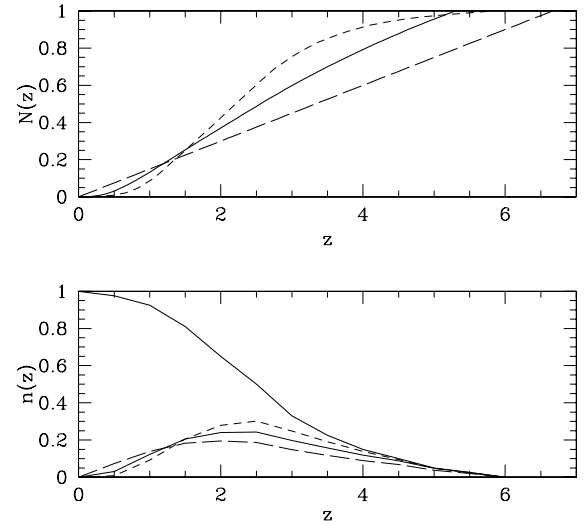


Figure 2. Top panel: the predicted cumulative fraction of GRBs as a function of redshift for various models studied here. The solid curve is the prediction for model II, the short-dashed curve is for model III and the long-dashed curve is for model IV. Note that models III and IV are normalized with respect to model II. Bottom panel: we illustrate the effect of folding in the detection efficiency of *Swift* as currently modelled by Mortsell & Sollerman (2005) on the differential number counts of GRBs. Despite the fall-off in sensitivity for $z > 6$ bursts as indicated by the thin solid curve, the SFR models will still be distinguishable for about 1000 detected bursts. The conventions for the line type are: thick solid, model I; short-dashed, model III; and long-dashed, model IV. Note that the bottom panel is for differential number counts and not cumulative number counts.

have a lower rate when the Universe is metal-rich at lower redshifts. This transition in the assumed GRB rate which is assumed to mimic the change in the mean metallicity of the Universe is taken to occur abruptly at $z = 3$. While metals are produced as a consequence of star formation, by construction, model IV bears no relation to a SFR – this was done for simplicity. The predictions for the expected redshift distribution of GRBs under these assumptions for model IV are also plotted in Fig. 2.

3 OBSERVATIONS OF GRBs

In order to predict the redshift distribution of GRBs, in addition to a phenomenological model for the star formation, we need to model the observed properties of the bursts, their number counts and luminosity distribution. The isotropically emitted photon flux P detected within an energy band $E_1 < E < E_2$ arising from a GRB at redshift z with a luminosity distance $d_L(z)$ is given by

$$P = \frac{(1+z) \int_{(1+z)E_1}^{(1+z)E_2} S(E) dE}{4\pi d_L^2(z)} \text{ erg s}^{-1}, \quad (2)$$

where $S(E)$ is the differential rest-frame photon luminosity of the source. The total burst luminosity in a given band can then be computed by integrating $ES(E)$ over the relevant energy range. Given a normalized LF $\psi(L)$ for GRBs, the burst rate of observed peak fluxes in the interval (P_1, P_2) is

$$\frac{dN}{dt} (P_1 \leq P < P_2) = \int_0^\infty dz \frac{dV(z)}{dz} \frac{R_{\text{GRB}}(z)}{1+z} \times \int_{L(P_1, z)}^{L(P_2, z)} dL' \psi(L') \epsilon(P), \quad (3)$$

where dV/dz is the co-moving volume element, $R_{\text{GRB}}(z)$ is the co-moving GRB rate density, $\epsilon(P)$ is the detector efficiency, and the $(1+z)^{-1}$ is the cosmological time dilation factor. The comoving volume element is given by

$$\frac{dV}{dz} = \frac{c}{H_0} \frac{\Delta\omega_s d_L^2(z)}{(1+z)^2 [\Omega_M(1+z)^3 + \Omega_K(1+z)^2 + \Omega_\Lambda]^{1/2}}, \quad (4)$$

where $\Delta\omega_s$ is the solid angle spanned by the survey. We adopted the detector efficiency function for BATSE provided by Band et al. (1993) to find our best-fitting parameters for the GRB LF.

GRBs have a broad LF when uncorrected for beaming effects; however, the data are insufficient at the present time to determine $\psi(L)$ directly from observations. Therefore we model the number counts as done by several authors (Porciani & Madau 2001; Guetta, Piran & Waxman 2005) by assuming that the burst luminosity distribution does not evolve with redshift. A simple parametric form is chosen for $\psi(L)$,

$$\psi(L) \propto \left(\frac{L}{L_0}\right)^\gamma \exp\left(-\frac{L}{L_0}\right), \quad (5)$$

where L denotes the peak luminosity in the 30–2000 keV energy range (rest-frame), γ is the asymptotic slope at the bright end, and L_0 is a characteristic cut-off luminosity. The normalization $\int_0^\infty \psi(L) dL = 1$ is used to define the constant of proportionality in equation (5). To describe the typical spectrum of a GRB, we use the form proposed by Band et al. (1993):

$$S(E) = A \times \begin{cases} \left(\frac{E}{100 \text{ keV}}\right)^\alpha \exp\left[-\frac{E(\beta - \alpha)}{E_b}\right] & E < E_b \\ \left(\frac{E_b}{100 \text{ keV}}\right)^{\alpha - \beta} \exp(\beta - \alpha) \left(\frac{E}{100 \text{ keV}}\right)^\beta & E \geq E_b. \end{cases}$$

The energy spectral indices, α and β , have the values -1 and -2.25 , respectively, measured from the bright BATSE bursts by Preece et al. (2000), with a spectral break at $E_b = 511$ keV. This description has been successfully calibrated against the observed number counts by Porciani & Madau (2001), and we adopt their calibration. They in turn used the off-line BATSE sample of Komers et al. (2000), which includes 1998 archival BATSE (‘triggered’ plus ‘non-triggered’) bursts in the 50–300 keV band.

We then optimize to determine the value of the three free parameters in the LF, γ and L_0 and the normalization constant, for the different star formation history models considered here. The overall quality of the best fit in the χ^2 squared sense is slightly better for our semi-analytic star formation model (model II) as it is slightly lower at high redshifts ($z > 5$) compared with the Porciani & Madau model. This is due to the fact that increasing star formation at high redshift causes the over-prediction of the number of bursts to be consistent with the faintest off-line BATSE counts. We find that increasing the steepness of the high-luminosity tail of $\psi(L)$ requires an increase in L_0 for the same value of χ^2 , implying that both models studied here need the presence of relatively high-luminosity events to reproduce the data. On comparing the properties of the LFs that provide the best fit for each SFR, we also find that the typical burst luminosity increases in models with larger amounts of star formation at early epochs, as also shown by Lloyd-Ronning, Fryer & Ramirez-Ruiz (2002). However, two of the star formation models considered here, models I and II, predict a very similar redshift distribution for GRBs. This is due to the fact that, although the star

formation for these models appears to diverge at $z > 7$, there is not much time elapsed at these high redshifts. Therefore we only show the predicted distribution for model II in Fig. 2. For our model III, with significantly lower amounts of star formation, fewer bursts are predicted at higher redshift compared with models I and II. Folding in the detection efficiency model curve for *Swift* (Mortell & Sollerman 2005), we predict the observed GRB redshift distribution for *Swift* (see Fig. 2).

4 RESULTS AND CONCLUSIONS

Our best-fitting parameters for the LF of GRBs, combined with BATSE number counts and the peak flux distribution for observed bursts, are then used to predict the redshift distribution for GRBs given a SFR model. The results for the SFR models and the metallicity-dependent rate model are plotted in Fig. 2. The predicted z -distributions for models I and II are very similar, and we show the curve only for model II. For both models I and II, we find that a very large fraction ~ 75 per cent of all GRBs originate at redshifts of 4 or lower. Our results are in excellent agreement with those reported recently by Guetta et al. (2005), where they studied the luminosity and angular distribution of long-duration GRBs, similarly modelling the SFR history (in particular see their fig. 3). Note that Guetta et al. utilized the relation between an assumed jet angular distribution and the GRB LF to predict the observed redshift distribution of bursts. They predict a local GRB detection rate for both the structured jet model and the universal jet model that is corrected for beaming. In this work we assume that the energy release in GRBs is isotropic. In an earlier calculation, Bromm & Loeb (2002) predicted a higher proportion of GRBs at higher redshifts compared with this work. This discrepancy arises because their treatment did not include a LF for GRBs and did not take into account the spectral energy distribution of GRBs. Unlike supernovae, GRBs are not standard candles, although there has been a recent claim of a tight correlation between the rest-frame peak energy and the rest-frame beaming-corrected gamma-ray energy release (Ghirlanda et al. 2004) which may allow them to be used as standard yard-sticks for cosmography purposes (Mortell & Sollerman 2005). The inclusion of the LF coupled with the Band function is a key ingredient that is needed in order to make robust predictions for the redshift distribution, even though there are considerable uncertainties. For model III with lower SFRs at high redshifts, we find a much smaller fraction of GRBs, only about ~ 10 per cent, to originate from $z > 4$. It is interesting to note that our toy model IV predicts (not surprisingly) a higher proportion of bursts, ~ 40 per cent, at $z > 4$.

Our model IV assumes that as low-mass galaxies are likely to have statistically lower metallicities, they are likely to contain more luminous GRBs than high-mass galaxies. Given that galaxies assemble hierarchically through mergers, then it is also possible that the highest redshift GRBs could be systematically more luminous owing to the lower mass and metallicity of their hosts. Such an effect motivates the metallicity dependence of the GRB rate assumed here. Additionally, star formation activity is likely to be enhanced in merging galaxies. In major mergers of gas-rich spiral galaxies, this enhancement takes place primarily in the inner kiloparsec. Metallicity gradients in the gas are likely to be smoothed out, by both mixing prior to star formation and supernova enrichment during the starburst. GRB luminosities could thus be suppressed in such well-mixed galaxies, making GRBs more difficult to detect in these most luminous objects, in which a significant fraction of all high-redshift star formation is likely to have occurred. Shocks in tidal tails associated with merging galaxies are also likely to precipitate the

³ The best-fitting $\chi^2/\text{d.o.f}$ for the models ranges from 0.76 to 1.05.

formation of high-mass stars, yet, as tidal tails are likely to consist of relatively low-metallicity gas, it is perhaps these less intense sites of star formation at large distances from galactic radii that are more likely to yield detectable GRBs. As more *Swift* bursts are followed up and their environments are better studied, this correlation will be testable.

Given the current uncertainties and our lack of knowledge of high-redshift star formation, if *Swift* detects a handful of bursts from beyond $z \sim 6$ with measured redshifts, these bursts might end up providing the only observational constraint on the star formation at these early epochs (see Fig. 2). We find that for a large number, of say, 1000 detected bursts, we will be able to discriminate between the various SFR models as illustrated in Fig. 2. Note that a more accurate and calibrated detection efficiency curve for *Swift* will be available after a few years of operation. The robustness of the assumption that the SFR is a good proxy for the GRB rate can also be tested further in the near future, as the uncertainties due to dust correction in determining SFRs are better understood and the host galaxies of GRBs are studied in more detail. As we explore here, the relation between the averaged metallicity of the Universe and the GRB rate might also prove to be testable with future observations of GRB host galaxies.

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